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Liquefaction induced by historic and prehistoric earthquakes in western Puerto Rico

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ABSTRACT

Dozens of liquefaction features in western Puerto Rico probably formed during at least three large earthquakes since A.D. 1300. Many of the features formed during the 1918 moment magnitude (M) 7.3 event and the 1670 event, which may have been as large as M 7 and centered in the Añasco River Valley. Liquefaction features along Río Culebrinas, and possibly a few along Río Grande de Añasco, appear to have formed ca. A.D. 1300–1508 as the result of a M ≥ 6.5 earthquake. We conducted reconnaissance along Río Culebrinas, Río Grande de Añasco, and Río Guanajibo, where we found and studied numerous liquefaction features, dated organic samples occurring in association with liquefaction features, and performed liquefaction potential analysis with geotechnical data previously collected along the three rivers. Our ongoing study will provide additional information regarding the age and size distribution of liquefaction features along the western, northern, and eastern coasts and will help to improve estimates of the timing, source areas, and magnitudes of earthquakes that struck Puerto Rico during the late Holocene.

Keywords: paleoseismology, paleoliquefaction, Quaternary fault behavior.

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INTRODUCTION

Significance

Puerto Rico, located within the tectonically active zone between the North America and Caribbean plates, is recognized as having a significant seismic hazard (Fig. 1; Asencio, 1980; McCann, 1985; Moya and McCann, 1992; Moya, 1999). Several large to very large earthquakes have struck Puerto Rico in the past 400 years. These include a moment magnitude (**M**) 7.5 event in 1943 located northwest of Puerto Rico, a **M** 7.3 event in 1918 centered in the Mona Passage, a **M** ~7.3 event in 1867 in the Anegada Passage, a **M** ~7.3 event in 1787 possibly related to the Puerto Rico Trench, and a **M** ~6 event in 1670 in western Puerto Rico (Fig. 1; McCann, 1985; Panagiotopoulos, 1995; Dolan et al., 1998; McCann et al., this volume; Doser et al., this volume). The 1918 earthquake reportedly induced liquefaction in the Añasco River Valley and generated a tsunami that struck the west coast of Puerto Rico, killing at least 114 persons and causing $4 million in damage (Fig. 2; Reid and Taber, 1919). The 1918 earthquake may also have induced liquefaction near Aguadilla to the north (Moya and McCann, 1991). Because the west coast is much more heavily populated now (486,800 in the Mayagüez-Aquadilla area according to the World-Gazetteer.com) than it was earlier in the century, a repeat of a 1918-type event would likely cause considerably more deaths and damage. Given its current population of almost 4 million with most people living in coastal areas subject to tsunami inundation and liquefaction, Puerto Rico is at significant risk from future large earthquakes.

Previous Related Work

Offshore structures that are potential sources of very large earthquakes include the Puerto Rico Trench, North Puerto Rico Slope fault zone, South Puerto Rico Slope fault zone, Septentrional fault zone, and faults associated with the Mona Passage, Virgin Islands trough, and Muertos trough (Fig. 1; Grindlay et al., 1997; Dolan et al., 1998). Offshore geophysical studies are under way to better define the active traces of these fault zones, particularly those along the western and southern coasts of Puerto Rico (see Grindlay et al., 2000, this volume). Possible onshore sources of damaging earthquakes include the Great Southern Puerto Rico fault zone and Great Northern Puerto Rico fault zone (Figs. 1 and 2). Shallow seismicity occurs below the central portion of the Great Southern Puerto Rico fault zone and in the southwestern corner of the island (Asencio, 1980; McCann, 1985; Joyce et al., 1987), suggesting that structures in these areas may be seismogenic. For much of the island, the youngest exposed rocks are Tertiary in age (Monroe, 1968; Glover, 1971; Seiders et al., 1972), making it difficult to determine the recency of faulting or ground shaking. Consequently, investigations of onshore faults have been limited (McCann, 1985; Moya and McCann, 1991). Field investigations of the Great Southern and Great Northern Puerto Rico fault zones found that they were active during the Tertiary and report predominantly thrust and left-lateral displacement (Glover and Mattson, 1960; Erikson et al., 1991). Other investigations conducted in the 1970s suggested that there might be evidence for late Quaternary deformation in the southern part of the island (Geomatrix Consultants, 1988). More recently, Prentice et al. (2000) identified and trenched the Lajas fault along the southern margin of the Lajas Valley and found evidence for Holocene movement (Fig. 2). With few exceptions, however, there is insufficient information to accurately assess the earthquake potential of onshore or offshore faults.

Paleoseismology, or the study of fault rupture and ground shaking as preserved in the late Quaternary geologic record, offers a time window of thousands of years that is well-suited for studying the behavior of fault systems and estimating rates of earthquake occurrence (Tuttle, 2001). Only a few paleoseismic studies have been conducted in the northern Caribbean but they have been successful at identifying active fault zones and liquefaction features resulting from strong ground shaking. On Hispaniola, paleoseismic studies of the Septentrional fault zone, a major left-lateral strike-slip fault related to the North America–Caribbean plate boundary, have estimated a slip rate of 9 ± 3 mm/yr and found evidence for a large earthquake ca. A.D. 1200 (Fig. 1; Prentice et al., 1993; Mann et al., 1998; Prentice et al., 2003). A study targeting areas where the Septentrional fault zone is buried by Holocene fluvial deposits found numerous historic and prehistoric liquefaction features. This paleoliquefaction study concluded that rupture of the fault ca. A.D. 1200 may have extended farther east than previously thought generating a M ~8 earthquake (Tuttle et al., 2003). These studies contribute to the understanding of earthquake hazards of Hispaniola and demonstrate the potential usefulness of paleoseismology in the tectonically active northeastern Caribbean.

Only one paleoliquefaction study has been previously conducted in Puerto Rico. Moya (1998), working with archaeologists from the Puerto Rico Institute of Culture, found sand dikes and sills intruding a cultural horizon and features at the Barrio Quemados. The archaeological site, thought to have been occupied from A.D. 1200 to 1500, is located a few kilometers east of Mayagüez on the fluvial plain of the Yaquez River (Fig. 2). Moya (1998) interpreted the sand dikes and sills as earthquake-induced liquefaction features that post-date the occupation of the site and that may have formed during the 1670 earthquake. Highly liquefiable sediments are known to occur in the San Juan area (Molinelli, 1985). Coastal plain sediments similar to those in San Juan have been mapped along most of the northern and southern coasts and in river valleys along the western and eastern coasts (Monroe, 1976). Liquefiable sediments have been identified in all the major river valleys of western Puerto Rico from geologic and geotechnical data (Moya and McCann, 1991). Site investigations, including measurement of shear wave velocities, have also found fluvial deposits in western Puerto Rico to be susceptible to liquefaction (Macari, 1994). Therefore, liquefiable sediments are present in river valleys along the coasts of Puerto Rico. If these sediments have been subjected to strong ground shaking, they

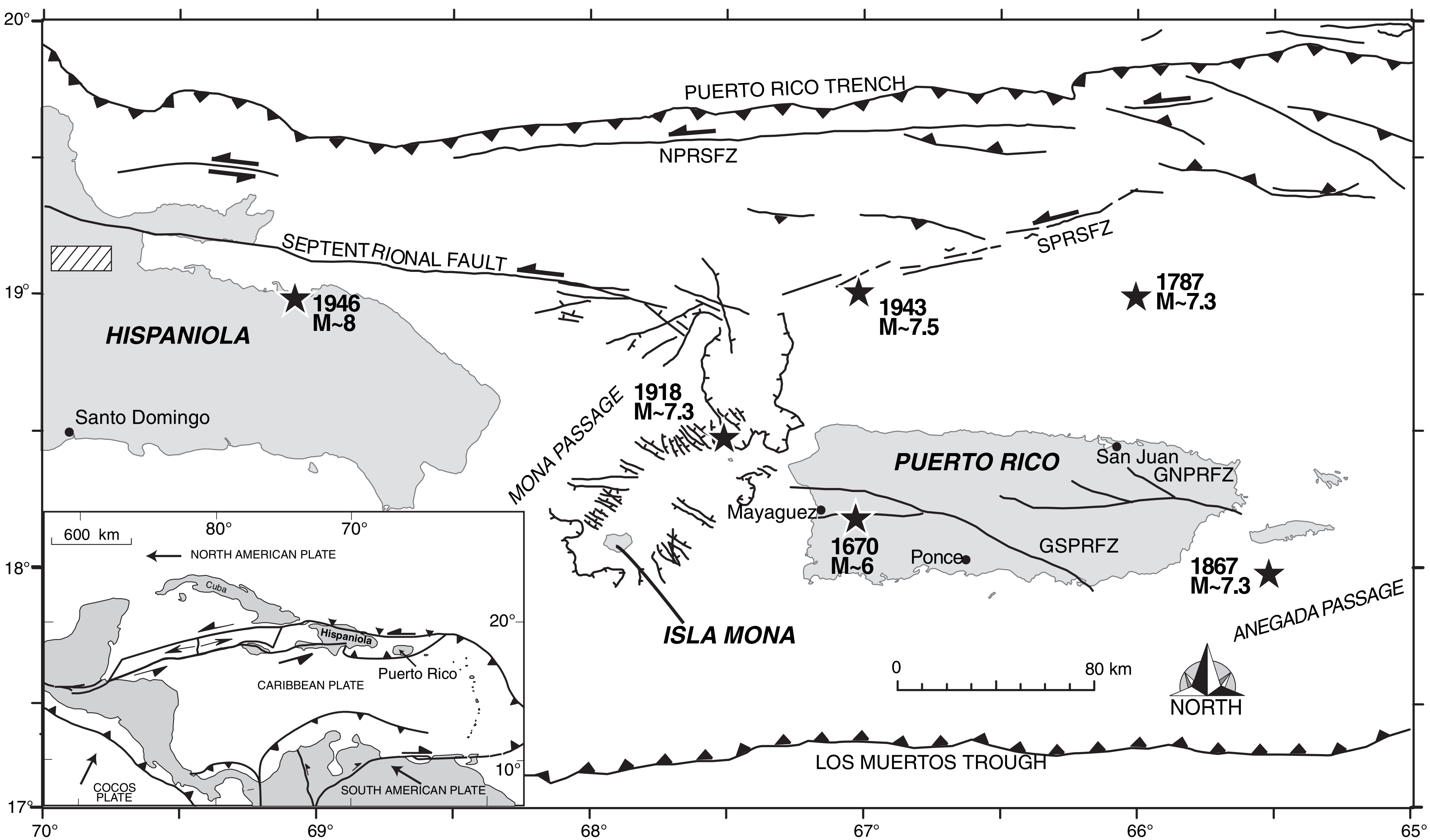

Figure 1. Location map of northeastern Caribbean in vicinity of Puerto Rico showing major onshore and offshore faults (Grindlay et al., 1997; Dolan et al., 1998) and locations of large historical earthquakes (1986 MIDAS catalogue; Dolan et al., 1998). GSPRFZ—Great Southern Puerto Rico fault zone; GNPRFZ—Great Northern Puerto Rico fault zone; NPRSFZ—Northern Puerto Rico Slope fault zone; SPRSFZ—Southern Puerto Rico Slope fault zone. Hispaniola study area, where liquefaction features may be related to 1946 (**M**) ~8 event and to 2–4 closely timed (**M**) 7–8 earthquakes ca. A.D. 1200, indicated by rectangle (Tuttle et al., 2003). Inset map shows plate-tectonic setting of greater Caribbean region.

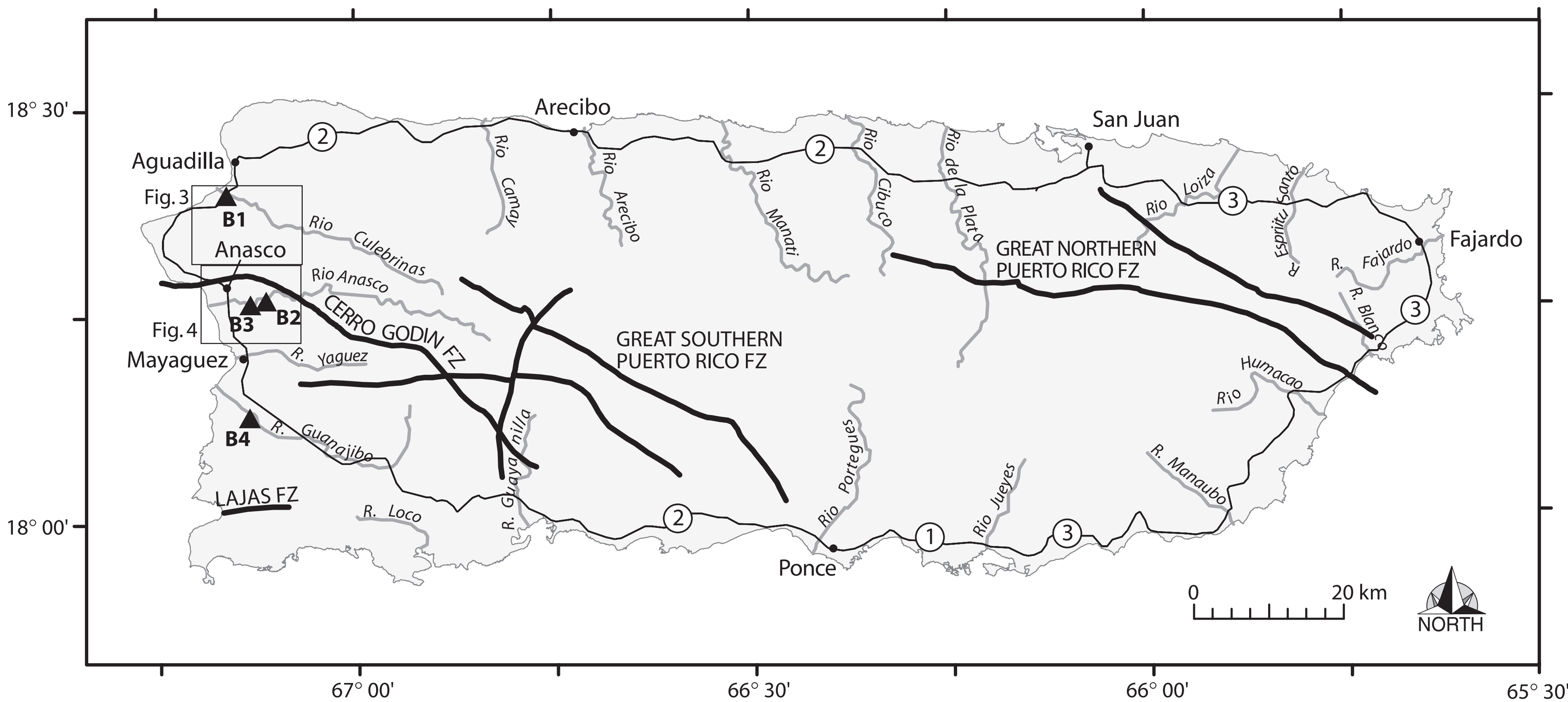

Figure 2. Map of Puerto Rico showing principal faults (Larue and Ryan, 1998; Jolly et al., 1998; Lao-Davila et al., 2000; Meltzer and Almy, 2000; Prentice et al., 2000), major rivers, borehole sites, labeled B1, B2, B3, and B4, and areas of Figures 3 and 4, labeled F3 and F4. FZ—fault zone.

may have liquefied, resulting in liquefaction features preserved in Holocene deposits.

Study Objectives

This paper presents results of an ongoing paleoliquefaction study in coastal areas of Puerto Rico. The purpose of the study is to help constrain the source areas of historic earthquakes and to estimate the timing, source areas, and magnitudes of prehistoric earthquakes. Toward this end, we have conducted (1) reconnaissance for, and documentation of, liquefaction features along three rivers, Río Culebrinas, Río Grande de Añasco, and Río Guanajibo, along the western coast of Puerto Rico, (2) radiocarbon dating of some of the liquefaction features we have found, and (3) liquefaction potential analysis of fluvial deposits.

METHODS OF INVESTIGATION

River Reconnaissance

During reconnaissance conducted in January and February 2000, we examined cutbanks along 14 km of Río Culebrinas, 11 km of Río Grande de Añasco, and 10 km of Río Guanajibo for earthquake-induced liquefaction features and other soft-sediment deformation structures related to ground shaking or faulting (Figs. 2, 3, and 4). Due to higher than normal river levels, cutbank exposure along Río Culebrinas, Río Grande de Añasco, and Río Guanajibo was limited to 4–5 m, 4 m, and 3 m, respectively. We found no evidence of faulting in late Holocene deposits; however, we did find and study many earthquake-induced liquefaction features (Tuttle et al., 2000). In addition, organic material was collected from host sediments for radiocarbon dating purposes. For sand dikes, we tried to find datable material close to their uppermost terminations. For sand blows, we tried to find datable material both above and below the vented deposit in order to establish minimum and maximum age constraints. All samples were later reviewed and the most useful ones for estimating ages of liquefaction features selected for radiocarbon dating by Beta Analytic, Inc.

Liquefaction Potential Analysis

In preparation for liquefaction potential analysis, we compiled borehole data, including blow counts, previously collected by the Puerto Rico Department of Transportation and Public Works at two bridge crossings of Río Grande de Añasco and one crossing each of Río Culebrinas and Río Guanajibo (Figs. 2, 3, and 4). The blow count (N), a measure of soil density, has been empirically related to liquefaction of sediment during actual earthquakes, with liquefaction susceptibility generally increasing with decreasing blow counts. The blow count values, taken from borehole logs, are the number of hammer blows, with a 140-lb hammer dropped a distance of 30 inches, required to advance a 2-inch split-barrel sampler approximately one foot (American Society for Testing and Materials, 1983). Simply comparing blow counts for the three rivers, sediments along the Río Grande de Añasco (N 2–15) appear to be the most susceptible to liquefaction; whereas sediments along the Río Guanajibo (N 17–25) appear to be least susceptible. It is important to take into account these differences in liquefaction susceptibility when interpreting the areal distribution of liquefaction features. We would have preferred to use borehole data collected at selected liquefaction sites, but in situ geotechnical testing was not possible given the scope of this study.

We applied the revised, simplified procedure (Seed and Idriss, 1982; Youd and Idriss, 1997) to evaluate liquefaction potential of fluvial sediments along Río Culebrinas, Río Grande de Añasco, and Río Guanajibo for various scenario earthquakes. The earthquakes we considered include the 1918 earthquake of **M** 7.3 located in the Mona Passage; the 1670 earthquake of **M** 7.0 generated by the Cerro Goden fault zone; the 1670 earthquake of **M** 6.5 or 7.5 generated by the Lajas fault zone; and a prehistoric (ca. A.D. 1300–1508) earthquake produced by an unknown fault in the Culebrinas River Valley, the Cerro Goden fault zone along the northern margin of the Añasco River Valley, or an offshore fault in the vicinity of the 1918 earthquake. For each borehole site, we determined whether representative sandy layers below the water table would be likely to liquefy during the scenario earthquakes. Estimates of peak ground acceleration for the earthquakes are based on ground-motion relations developed for California (Boore et al., 1997). This assessment would benefit from additional analysis using attenuation relations developed specifically for Puerto Rico or the northeastern Caribbean.

RESULTS OF INVESTIGATIONS

River Reconnaissance

Results of the search for and dating of liquefaction features in western Puerto Rico are summarized in Tables 1 and 2 and illustrated on Figures 3 and 4. Along Río Culebrinas, we found twenty-seven liquefaction features at ten sites. Liquefaction features include sand dikes up to 23 cm wide and one, possibly two, sand blow deposits. Along Río Grande de Añasco, we found thirty liquefaction features at eighteen sites, including sand dikes up to 16 cm wide and two, possibly five, sand blows. The five largest dikes occur at sites 2, 10, 11, 17, and 18 located between 3.5 and 4.5 km from the coast. Several of the liquefaction features are discussed below.

Río Culebrinas

At site Río Culebrinas 1 (RC1), several dikes extend into the base of a paleosol characterized by soil structure and organic accumulation (Fig. 5). The largest dike is discontinuous as it crosses the paleosol but appears to widen to form a vent structure within the top of the paleosol and to broaden into the base of an overlying sand layer. The sand layer is of

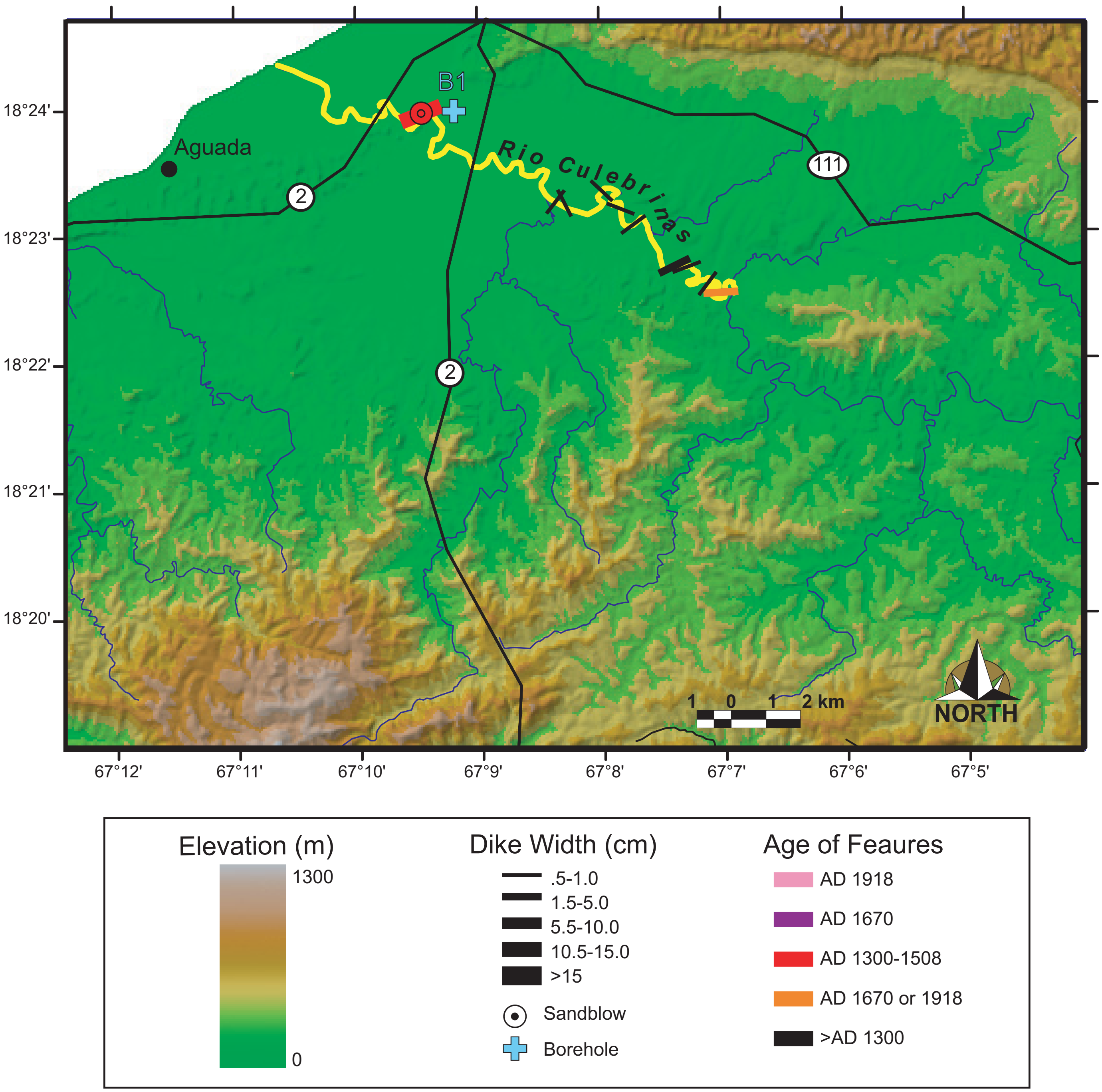

Figure 3. Digital elevation model of the Culebrinas River Valley showing locations, sizes, and estimated ages of earthquake-induced liquefaction features. Yellow line indicates portion of river surveyed. Borehole location also indicated. See Figure 2 for location of area shown.

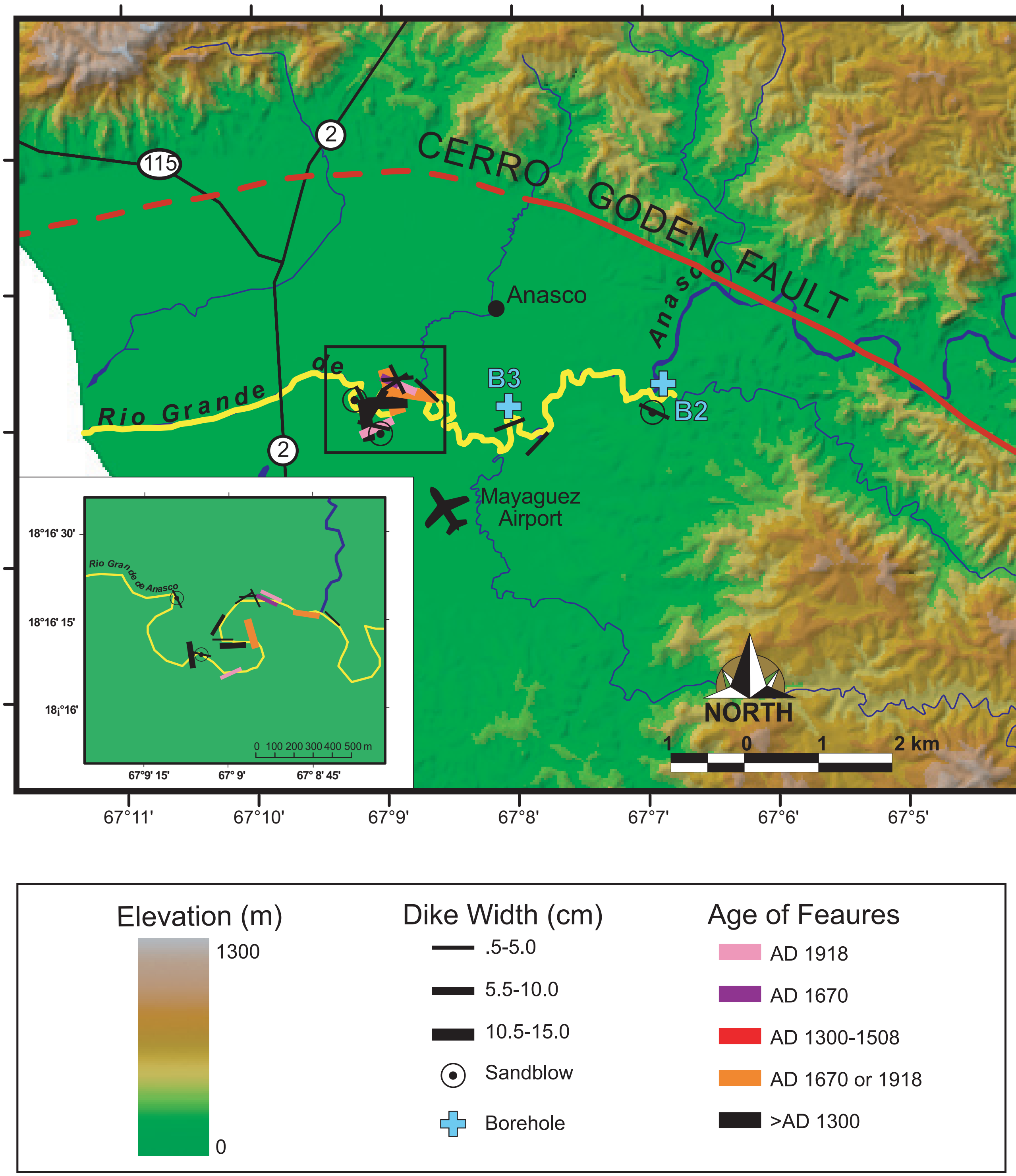

Figure 4. Digital elevation model of the Añasco River Valley showing locations, sizes, and estimated ages of earthquake-induced liquefaction features. Borehole location also indicated. Inset is enlargement of area with numerous liquefaction features. See Figure 2 for location of area shown.

limited lateral extent and pinches out away from the sand dike. The sand layer is interpreted as a sand blow that was deposited on the paleosol that would have been at the surface at the time. Radiocarbon dating of charcoal located 10 cm below the base of the sand blow and within the paleosol yielded a calibrated age of A.D. 1300–1370, 1380–1430 (Table 2). The charcoal sample provides a close maximum age for the liquefaction features and indicates that they formed after A.D. 1300, and possibly after A.D. 1430. Since there is no large earthquake recorded by the Spanish following colonization in A.D. 1508 and prior to the earthquake in A.D. 1670 (McCann et al., this volume), the event that induced liquefaction at this site is estimated to have occurred between A.D. 1300 and A.D. 1508.

At site Río Culebrinas 2 (RC2), several dikes filled with pebbly, coarse sand are exposed in the river cutbank. The largest dike (6 cm wide) extends ~3 m above the river level where it crosscuts a paleosol and broadens into the base of a pebbly sand layer that pinches out away from the sand dike. The sand layer is interpreted as a sand blow. A piece of charcoal was collected from the paleosol 14 cm below the overlying sand blow. Radiocarbon dating of the sample indicates that the sand blow and related sand dike formed after A.D. 1640 (Table 2). Radiocarbon dating at sites RC3 and RC6, where only sand dikes were found, indicates that these liquefaction features formed since A.D. 1300. It appears that at least a 700 yr record of fluvial sedimentation and strong ground shaking is preserved in the upper 4–5 m of sediments along the Río Culebrinas. By inference, we estimate that liquefaction

TABLE 1. RESULTS OF RECONNAISSANCE AND RADIOCARBON DATING OF LIQUEFACTION FEATURES

Site name	Latitude (decimal degrees)	Longitude (decimal degrees)	Thickness of sand blows (cm)	Width of sand dikes (cm)	Strike and dip of largest sand dikes	Preliminary age estimate of features (A.D.)
Río Culebrinas						
1	18.401183	67.158133	20	23, 10, 7, 3, 3, 2	N68°E, 80°NW N38°E, 78°NW N83°E, 75°NW	1300–1508
2	18.377583	67.117267		6, 2	N88°E, vertical	1670
3	18.378450	67.119000		4, 1.5	N38°E, vertical	>1300
4	18.380700	67.121883		4.5	N68°E, 78°NW	>1300
5	18.381117	67.123750		8	N64°E, vertical	>1300
6	18.386333	67.129100		3, 2, 1.5, 1.5, 1.5	N53°E, 81°NW	>1300
7	18.388417	67.130917		3	N68°W, vertical	>1300
8	18.390667	67.133450		5	N47°W, 87°NE	>1300
9	18.389150	67.138500		1.5	N27°W, vertical	>1300
10	18.389333	67.139833		3, 2, 1, 0.5, 0.5	N38°E, vertical	>1300
Río Grande de Añasco						
1	18.271940	67.153040	8	3.5	N27°W, vertical	>1300
2	18.269710	67.152690		13, 1	N7°W, vertical	>1300
3	18.268790	67.151670	0.5	3, 2.5	N77°W, vertical	>1300
4	18.268650	67.151420		8, 4.5	N66°E, 86°SE N23°E, vertical	1918
5	18.271600	67.115200				>1300
6	18.270300	67.115800	3.5	5	N67°W, 80°SW	>1300
7	18.266333	67.130733		3, 1, 1	N43°E, 82°SE	>1300
8	18.268700	67.134333		3	N71°E, 80°NW	>1300
9	18.272983	67.144783		3	N45°W, vertical	>1300
10	18.272950	67.146450		13, 4, 1	N82°W, vertical N27°W, 88°SW	1670 or 1918
11	18.274050	67.148350	12	9, 6	N68°W, 70°NE N57°W, 81°NE	1670 and 1918
12	18.274333	67.148600		4	N27°W, vertical	>1300
13	18.274467	67.148667		2, 1	N83°E, 72°NW	>1300
14	18.274000	67.148983		4	N57°E, vertical	>1300
15	18.271433	67.151567		6	N33°E, vertical	>1300
16	18.271567	67.149800	6	1	N89°E, vertical	>1300
17	18.271783	67.150117		15	N87°W, vertical	>1300
18	18.273150	67.149233		16	N14°W, vertical	1670 or 1918
Río Guanajibo						
1	18.138833	67.141083		3	N48°E, 80°SE	>1300
2	18.156933	67.165833		0.5	N87°W, vertical	>1300

features documented at eight other sites along the river, for which we have no radiocarbon dating data, formed since A.D. 1300.

Río Grande de Añasco

At site Río Grande de Añasco 11 (RGA11), several sand dikes extend 0.63 m above the river level and broaden slightly into the base of a 12-cm-thick sand layer (Fig. 6). The sand layer fines and thins away from the sand dikes and portions of the sand layer appear to have been eroded. These characteristics suggest that the layer is a sand blow deposit. In addition, there is a second generation of sand dikes that crosscuts the sand blow deposit. One of the dikes extends to 1.13 m above the river level (Fig. 7). Charcoal collected 10 cm below the sand blow deposit indicates that the first generation of liquefaction features formed after A.D. 1640; whereas, charcoal collected above the sand blow and 10 cm below the tip of a younger sand dike indicates that the second generation liquefaction features formed after A.D. 1670 (Table 2). Therefore, it appears that both generations of liquefaction features formed in the past 400 yr.

TABLE 2. RESULTS OF RADIOCARBON DATING OF SAMPLES COLLECTED AT LIQUEFACTION SITES ALONG RÍO CULEBRINAS, RÍO GRANDE DE AÑASCO, AND RÍO GUANAJIBO

Site sample	Lab sample	$^{13}C/^{12}C$ ratio	^{14}C age (1σ, yr B.P.)*	Cal yr A.D./B.C. (2σ)†	Probability distribution	Sample description	Earthquake age constraint
(1) RC1-C3	Beta-129692	–21.7	560 ± 40	A.D. 1300–1370 A.D. 1380–1430	0.526 0.474	charcoal 10 cm below sand blow; from paleosol; 1.4 m awl	>A.D. 1300
(2) RC1-W1	Beta-146689	–26.4	160 ± 80	A.D. 1530–1540 A.D. 1640–1960	0.008 0.992	possibly recent deposit; wood ~1 m below top of dike; just awl	
(3) RC2-C1	Beta-146690	–26.5	200 ± 40	A.D. 1640–1700 A.D. 1720–1810 A.D. 1830–1880 A.D. 1920–1950	0.267 0.537 0.049 0.146	charcoal 14 cm below top of dike; 2.86 m awl	>A.D. 1640
(4) RC3-C2	Beta-146691	–16.2	600 ± 40	A.D. 1300–1410	1.000	charcoal adjacent to top of sand dike; 1.39 m awl	>A.D. 1300
(5) RC6-C3	Beta-146692	–18.2	460 ± 40	A.D. 1330–1340 A.D. 1400–1490 A.D. 1500–1510 A.D. 1600–1610	0.001 0.985 0.001 0.013	charcoal 27 cm below top of upper-most sand dike; 2.28 m awl	>A.D. 1300
(6) RGA2-C2	Beta-129693	–27.2	100 ± 40	A.D. 1680–1740 A.D. 1750–1760 A.D. 1800–1940 A.D. 1950–1955	0.290 0.025 0.657 0.028	charcoal few cm above top of dike; 1.91 m awl	
(7) RGA4-C1	Beta-129691	–11.4	110 ± 40	A.D. 1680–1760 A.D. 1770–1780 A.D. 1800–1940 A.D. 1950	0.336 0.005 0.632 0.027	charcoal 6 cm below top of dike; 1.6 m awl	>A.D. 1680
(8) RGA4-C3	Beta-129694	–17.8	420 ± 40	A.D. 1420–1520 A.D. 1570–1630	0.843 0.157	charcoal 23 cm below top of dike; 1.43 m awl	>A.D. 1420
(9) RGA4-O4	Beta-146693	–26.7	90 ± 40	A.D. 1680–1740 A.D. 1750–1760 A.D. 1800–1940 A.D. 1950	0.282 0.009 0.678 0.032	possibly recent deposit; leaves 1.77 m below top of dike; just awl	
(10) RGA10-C1	Beta-146694	–28.5	190 ± 40	A.D. 1640–1700 A.D. 1720–1820 A.D. 1830–1880 A.D. 1910–1950	0.235 0.532 0.074 0.158	charcoal 40 cm below top of dike; 0.4 m awl	>A.D. 1640
(11) RGA11-C3	Beta-146695	–28.4	130 ± 40	A.D. 1670–1780 A.D. 1800–1910 A.D. 1910–1940 A.D. 1950	0.405 0.429 0.147 0.019	charcoal 10 cm below top of younger sand dikes; 1.03 m awl	>A.D. 1670
(12) RGA11-C5	Beta-146696	–28.0	190 ± 40	A.D. 1640–1700 A.D. 1720–1820 A.D. 1830–1880 A.D. 1910–1950	0.235 0.532 0.074 0.158	charcoal 10 cm below sand blow; 0.53 m awl	>A.D. 1640
(13) RGA18-C1	Beta-146697	–31.4	200 ± 50	A.D. 1530–1540 A.D. 1640–1710 A.D. 1720–1890 A.D. 1910–1950	0.004 0.268 0.583 0.145	charcoal 1.1 m below top of sand dike; 0.2 m awl	>A.D. 1640

Note: RC—Río Culebrinas; RGA—Río Grande de Añasco; RG—Río Guanajibo; awl—above water level.
*Conventional radiocarbon ages in years before present (1950) determined by Beta Analytic, Inc.
†Calibrated calendar age ranges determined with CALIB Rev. 4.3, Method B and rounded to the nearest decade (Stuiver et al., 1998).

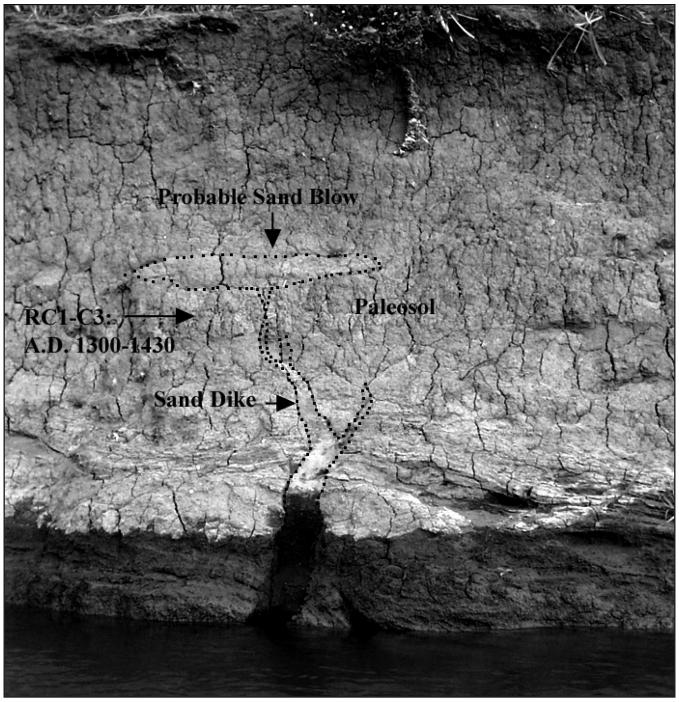

Figure 5. Photograph of sand dike and related sand blow at site RC1. Charcoal from a paleosol crosscut by sand dike and overlain by sand blow provides close maximum age of A.D. 1300–1430.

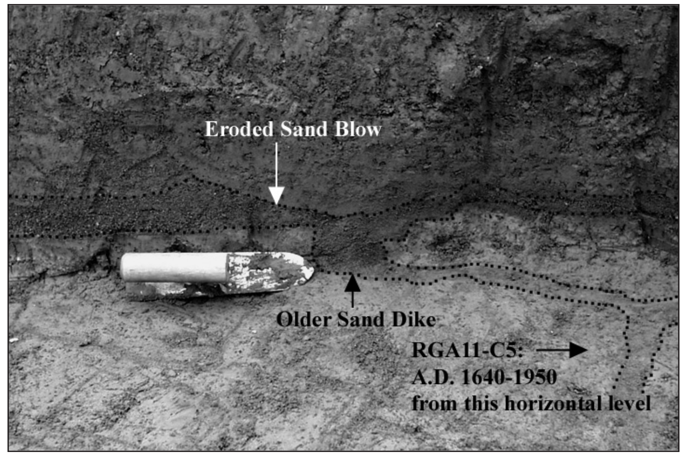

Figure 6. Photograph of sand dike and related sand blow at site RGA11. Upper portion of sand blow appears eroded.

At nearby site RGA10, a 13-cm-wide sand dike extends 0.8 m above the river level and terminates within a paleosol. Charcoal collected 40 cm below the tip of the dike indicates that it formed after A.D. 1640 (Table 2). Similarly, at RGA18, a 16-cm-wide dike extends 1.3 m above the river. Charcoal collected 1.1 m below the tip of the dike indicates that it formed after A.D. 1530, and more likely after A.D. 1640. At RGA4, two sand dikes extend 1.66 m and 1.40 m above the river level. Pieces of charcoal collected 6 cm and 23 cm below the tip of the uppermost sand dike yield stratigraphically consistent results and indicate that the dikes formed after A.D. 1680. It appears that at least a 600–700 yr geological record is preserved in the upper 4 m of cutbanks along the Río Grande de Añasco. We infer that liquefaction features documented at other sites along the river, but for which we have no radiocarbon data, formed since A.D. 1300 (Fig. 8).

Río Guanajibo

Along Río Guanajibo located ~6 km south of Mayagüez, we found only two small dikes at two different sites (Fig. 2; Table 1). The dikes are filled with medium sand and fine sandy silt. No organic material was found at either liquefaction site that could help to constrain the age of the features. Based on dating of materials along Río Grande de Añasco, deposits exposed along the Río Guanajibo are probably less than 700 yr old. Therefore, we infer that the two sand dikes along Río Guanajibo also formed since A.D. 1300. It appears that earthquake-induced liquefaction was less extensive and less severe along the Río Guanajibo than along rivers farther north.

Results of Liquefaction Potential Analysis

The results of liquefaction potential analysis for the scenario earthquakes described above are presented in Tables 3–6. The 1918 **M** 7.3 earthquake, thought to have been centered in the Mona Passage, reportedly induced liquefaction in the Añasco River Valley (Reid and Taber, 1919). The results of our analysis are consistent with this observation (Table 3). However, it seems unlikely that the 1918 earthquake induced liquefaction along Río Culebrinas. This event would have had to be about **M** 7.5 and located closer to shore to do so (Table 6). Therefore, the post–A.D. 1640 liquefaction features on the Culebrinas probably formed during the 1670 earthquake, as did some of the features along the Añasco. The 1670 earthquake is thought to have been centered in southwestern Puerto Rico and to have induced liquefaction in the Yaquez River Valley (Moya, 1998). If the 1670 earthquake were centered in the Lajas Valley, a location of Holocene-age faulting (Prentice et al., 2000), it would have to be of at least **M** 6.5 to induce liquefaction along the Añasco (Table 4). Such an event, however, would not induce liquefaction along the Culebrinas, even if it were of **M** 7.5. If generated by the Cerro Goden fault zone, the 1670 earthquake would have to be of **M** 7 to induce liquefaction along both the Añasco and the Culebrinas (Table 5). Therefore, the 1670 earthquake may have been of **M** ~7 and more likely centered in or near the Añasco River Valley than in the Lajas Valley.

With the available data, we cannot yet resolve the source area of an earthquake that induced liquefaction along Río Culebrinas between A.D. 1300–1508. Our analysis suggests that if the earthquake were generated by a fault in the Culebrinas River

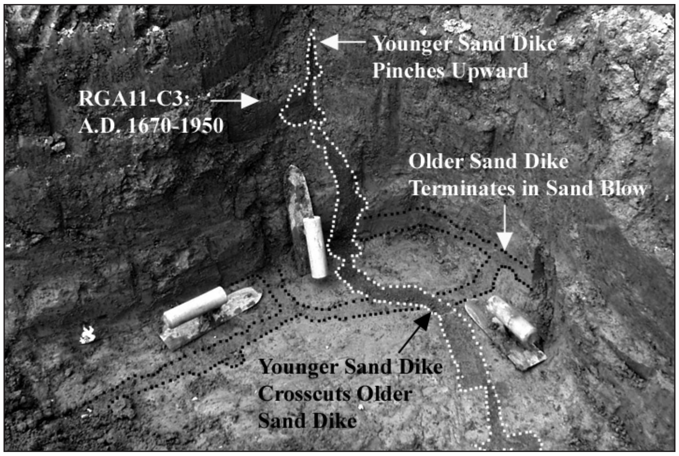

Figure 7. Photograph of crosscutting relations of two generations of sand dikes at site RGA11.

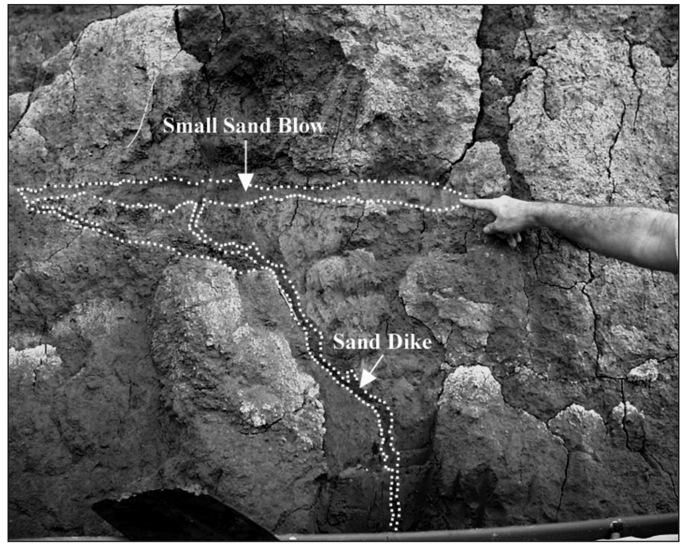

Figure 8. Photograph of small sand dike and related sand blow at site RGA16.

Valley, it could have been as small as **M** 6.5 and still induce liquefaction locally (Table 6). If generated by the Cerro Goden fault zone, the event would have to be of **M** ≥ 7. Alternatively, if produced by an offshore source like that of the 1918 earthquake, the A.D. 1300–1508 event would have to be at least **M** 7.5 and located within 30 km of the shoreline to induce liquefaction along Río Culebrinas (Table 6).

SUMMARY AND CONCLUSIONS

During river reconnaissance in western Puerto Rico, we found and studied twenty-seven liquefaction features along Río Culebrinas, thirty features along Río Grande de Añasco, and two features along Río Guanajibo. The liquefaction features included a few small sand blows and many small to medium-sized sand dikes. Many of the liquefaction features probably formed during the 1918 or 1670 earthquakes (Tables 1 and 2). Those liquefaction features for which we have maximum age constraint of A.D. 1640 could have formed during either of the 1670 or 1918 events (see Table 7 for a summary of our interpretations). Those features with maximum age constraint of 1670 or later probably formed during the 1918 earthquake. At least one liquefaction feature on the Río Culebrinas formed between A.D. 1300 and 1508. Although additional earthquakes cannot be ruled out, other liquefaction features documented along the three rivers probably formed during one of these three earthquakes.

Liquefaction potential analysis of sandy sediments along Río Culebrinas, Río Grande de Añasco, and Río Guanajibo was used to evaluate several scenario earthquakes (Table 7). The results of our analysis are consistent with the observation that the 1918 earthquake induced liquefaction in the Añasco River Valley. Our analysis suggests that the 1670 earthquake, which appears to have produced liquefaction features along both Río Grande de Añasco and Río Culebrinas, may have been of **M** ~7 and located in or near the Añasco River Valley. The source and magnitude of an event ca. A.D. 1300–1508 that induced liquefaction along Río Culebrinas is uncertain, but our analysis indicates that, even if it were a local event, it was probably of **M** ≥ 6.5.

Reconnaissance was conducted when river levels were not especially low. Liquefaction features related to prehistoric earthquakes may occur deeper in the section than was exposed at the time of reconnaissance. Therefore, we think that it would be worthwhile to resurvey at least portions of Río Culebrinas, Río Grande de Añasco, and Río Guanajibo when water levels are lower than they were in January and February 2000. Reconnaissance of river cutbanks and liquefaction potential analysis of fluvial sediments along the northern and eastern coasts of Puerto Rico are currently under way. Additional information regarding the age and size distribution of liquefaction features will help to improve estimates of the timing, source area, and magnitudes of earthquakes that struck Puerto Rico during the late Holocene.

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TABLE 3. THE 1918 EARTHQUAKE OF M 7.3

Site/borehole (map reference)	Magnitude @ distance (km)	amax	Depth to susceptible sediment (ft)	Blow count $N_{1(60)}$	Cyclic stress ratio	Results*
Culebrinas RT-2 (B1)	M7.3@40	0.15	20	16	0.12	N
Añasco RT-406 (B2)	M7.3@50	0.13	35	7	0.09	L
	M7.3@50	0.13	40	6	0.09	L
	M7.3@50	0.13	15	1	0.06	N
	M7.3@50	0.13	15	5	0.06	L
	M7.3@50	0.13	20	8	0.07	N
	M7.3@50	0.13	10	10	0.04	N
	M7.3@50	0.13	15	2	0.06	N
	M7.3@50	0.13	15	13	0.14	N
	M7.3@50	0.13	20	12	0.09	N
	M7.3@50	0.13	15	15	0.15	N
Añasco RT-430 (B3)	M7.3@40	0.15	20	3	0.08	L
	M7.3@40	0.15	25	13	0.11	N
	M7.3@40	0.15	5	13	0.06	N
	M7.3@40	0.15	7	10	0.08	N
	M7.3@40	0.15	10	4	0.09	L
	M7.3@40	0.15	35	4	0.11	L
	M7.3@40	0.15	45	6	0.11	L
	M7.3@40	0.15	15	6	0.11	L
	M7.3@40	0.15	20	12	0.11	N
Guanajibo RT-114 (B4)	M7.3@50	0.13	17	2	0.08	L
	M7.3@50	0.13	25	15	0.09	N
	M7.3@50	0.13	17	8	0.07	N
	M7.3@50	0.13	20	19	0.08	N

*L—liquefaction likely; M—liquefaction marginal; N—liquefaction not likely.

TABLE 4. THE 1670 EARTHQUAKE IF M 6.5 OR M 7.5 AND PRODUCED BY THE LAJAS VALLEY FAULT ZONE

Site/borehole (map reference)	Magnitude @ distance (km)	amax	Depth to susceptible sediment (ft)	Blow count $N_{1(60)}$	Cyclic stress ratio	Results*
Culebrinas RT-2 (B1)	M6.5@40	0.10	20	16	0.08	N
	M7.5@40	0.17	20	16	0.14	N
Añasco RT-406 (B2)	M6.5@30	0.12	35	7	0.09	N
	M6.5@30	0.12	40	6	0.08	N
	M6.5@30	0.12	10	5	0.05	N
	M6.5@30	0.12	15	1	0.06	N
	M6.5@30	0.12	15	5	0.06	N
	M6.5@30	0.12	20	8	0.06	N
	M6.5@30	0.12	10	10	0.04	N
	M6.5@30	0.12	15	2	0.05	N
	M6.5@30	0.12	15	13	0.14	N
	M6.5@30	0.12	20	12	0.09	N
	M6.5@30	0.12	15	15	0.14	N
Añasco RT-430 (B3)	M6.5@30	0.12	20	3	0.07	N
	M6.5@30	0.12	25	13	0.09	L
	M6.5@30	0.12	5	13	0.05	N
	M6.5@30	0.12	7	10	0.06	N
	M6.5@30	0.12	10	4	0.08	L
	M6.5@30	0.12	35	4	0.09	L
	M6.5@30	0.12	45	6	0.09	L
	M6.5@30	0.12	15	6	0.09	L
	M6.5@30	0.12	20	12	0.09	L
Guanajibo RT-114 (B4)	M6.5@15	0.21	17	2	0.13	L
	M6.5@15	0.21	25	15	0.14	N
	M6.5@15	0.21	17	8	0.12	M
	M6.5@15	0.21	20	19	0.12	N

*L—liquefaction likely; M—liquefaction marginal; N—liquefaction not likely.

TABLE 5. THE 1670 EARTHQUAKE IF M 7 AND PRODUCED BY THE CERRO GODEN FAULT ZONE

Site/borehole (map reference)	Magnitude @ distance (km)	amax	Depth to susceptible sediment (ft)	Blow count $N_{1(60)}$	Cyclic stress ratio	Results*
Culebrinas RT-2 (B1)	M7@15	0.27	20	16	0.22	L
Añasco RT-406 (B2)	M7@5	0.49	35	7	0.34	L
	M7@5	0.49	40	6	0.33	L
	M7@5	0.49	10	5	0.18	L
	M7@5	0.49	15	1	0.22	L
	M7@5	0.49	15	5	0.22	L
	M7@5	0.49	20	8	0.25	L
	M7@5	0.49	10	10	0.17	L
	M7@5	0.49	15	2	0.21	L
	M7@5	0.49	15	13	0.54	L
	M7@5	0.49	20	12	0.35	L
	M7@5	0.49	15	15	0.55	L
Añasco RT-430 (B3)	M7@5	0.49	20	3	0.27	L
	M7@5	0.49	25	13	0.36	L
	M7@5	0.49	5	13	0.20	L
	M7@5	0.49	7	10	0.25	L
	M7@5	0.49	10	4	0.29	L
	M7@5	0.49	35	4	0.36	L
	M7@5	0.49	45	6	0.34	L
	M7@5	0.49	15	6	0.33	L
	M7@5	0.49	20	12	0.36	L
Guanajibo RT-114 (B4)	M7@15	0.27	17	2	0.17	L
	M7@15	0.27	25	15	0.19	N
	M7@15	0.27	17	8	0.15	L
	M7@15	0.27	20	19	0.16	N

*L—liquefaction likely; M—liquefaction marginal; N—liquefaction not likely.

TABLE 6. THE PREHISTORIC EARTHQUAKE THAT INDUCED LIQUEFACTION ALONG THE RIO CULEBRINAS

Earthquake source	Magnitude @ distance (km)	amax	Depth to susceptible sediment (ft)	Blow count $N_{1(60)}$	Cyclic stress ratio	Results*
Local source in the Rio Culebrinas River Valley	M6.25@5	0.33	20	16	0.27	N
	M6.5@5	0.37	20	16	0.30	L
Cerro Goden fault zone	M6.75@15	0.24	20	16	0.19	N
	M7@15	0.27	20	16	0.22	L
1918 source area	M7.3@30	0.19	20	16	0.15	N
	M7.3@40	0.15	20	16	0.12	N
	M7.5@30	0.21	20	16	0.17	L
	M7.5@40	0.17	20	16	0.14	N

*L—liquefaction likely; M—liquefaction marginal; N—liquefaction not likely.

TABLE 7. SUMMARY OF INTERPRETATIONS FROM FIELD OBSERVATIONS AND ANALYSIS OF SCENARIO EARTHQUAKES

River names	Mona Passage M ~7.3 1918	Cerro Godin fault zone M ~7.0 1670	Northwestern Puerto Rico M $\geq$ 6.5 1300–1508
Río Culebrinas	No Liquefaction	Liquefaction	Liquefaction
Río Grande de Añasco	Liquefaction	Liquefaction	No Liquefaction
Rio Yaquez	Unknown	Liquefaction	Unknown
Río Guanajibo	Liquefaction for at least one of these events		

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